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On the Stress-Shear Relation Near a Turbulent Air-Sea Interface

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ABSTRACT

The average wind profile versus height for a "nearly flat" water surface roughened by capillaries is logarithmic down to a certain point, and must then approach the surface velocity smoothly at the time averaged surface. For lack of data, we hypothesize the form of the "interfacial sublayer" to be that of Liu et al. (1979) for smooth flow with a modification in the dominant scale size to accommodate the transition from smooth to rough flow. The result implies that the surface shear increases with applied stress until roughness sets in. Then, owing to increased turbulence at the interface, the shear may reach a maximum and decrease. If this were to hold true, there would be important implications for air-sea coupling in general, and wind wave generation mechanisms in particular.

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1. INTRODUCTION

The relation between tangential stress τ and shear $u'(z)$ at an air-sea interface is complicated by the presence of turbulence, small scale surface roughness and atmospheric stratification of humidity and temperature. In this note we will consider the case of neutral stability for simplicity. The importance of stratification upon surface fluxes has been demonstrated elsewhere (e.g., Liu, et al. 1979; Kondo, 1975). For viscous-dominated flow (i.e. laminar flow) we expect $\tau = \rho\nu\, u'(z)$, where ρ is the density of air, ν the kinematic viscosity, u the horizontal wind velocity, z the height, and prime denotes differentiation with respect to the argument. For turbulent flow above a smooth surface, the stress is maintained by eddy transport of momentum, with a mixing length proportional to z (with $z = 0$ at the surface). At sufficiently large distances from the surface, the classical logarithmic profile emerges:

$$u - u_s = \frac{u_*}{k} \log z/z_0, \tag{1}$$

where $k = 0.4$ is Von Karman's constant, u_s is the surface velocity,

$$z_0 = \beta\nu/u_* , \tag{2}$$

u_* is the friction velocity

$$u_* = \sqrt{\tau/\rho} , \tag{3}$$

and $\beta = 0.11$ (Schlichting, 1960; Landau and Lifschitz, 1959). According to (2), as the stress increases, the scale size z_0 decreases. For a real air-sea interface, however, as the stress increases, small high frequency waves roughen the surface.

Simultaneously, there emerges a new stress transfer mechanism: the form drag of the roughness waves (i.e., the interaction of pressure fluctuation and Reynolds stress with wave slope). At large distances from the surface, (1) still holds, but with z_0 replaced by a roughness scale z_r (Liu, et al., 1979; Kondo, 1975). On dimensional grounds, one expects for rough flow

$$z_0 \rightarrow z_r = m\, u_*^2/g \tag{4}$$

(Charnock, 1955; Kraus, 1972) with m between .007 and .060. This scale size increases in proportion to the stress.

The remainder of this note will address two gaps evident above: the first is the region from $z = 0$ to $z >> z_0$, where (1) holds; the second is the transition from (2) to (4) for the dominant scale size (i.e., the transition from a smooth to a rough interface).

We will refer to a smooth, continuous horizontal wind profile $u(z)$ which is in fact a time average or ensemble average of a turbulent, fluctuating wind. When roughness emerges, results to be derived should be descriptive of the region $z \gtrsim z_r$. Points closer than this to the mean surface level $z = 0$ may be submerged part of the time. Our goal is not to predict a single profile with precision, but to examine in general the consequences of some apparently reasonable hypotheses.

Whether the surface is smooth or rough it is evident that the wind profile must break away from (1) at some point and approach U_s continuously as $z \rightarrow 0$ (See Figure 1). The implications of this break away are of primary interest here. For smooth flow, Liu, et al. (1979) proposed a "surface renewal model" layer for $0 < z < 47\ \nu/u_*$, which

agrees with data and joins smoothly to the logarithmic profile. They refer to this layer as the "interfacial sublayer."

In this paper we hypothesize that for rough flow, the break away from the logarithmic profile occurs in a way similar to that proposed by Liu, et al. (1979). We also propose a simple analytic expression for $z_0(u_*)$ and demonstrate that these hypotheses lead to an interesting prediction: that with increasing stress, the shear near the surface may increase to a maximum and then fall off. This would be a result of surface roughness increasing at such a rate that more stress could be transmitted to the surface with less shear.

2. A GENERALIZED WIND PROFILE

In equations (5) and (6) we make two hypotheses concerning the wind profile:

$$\frac{u - u_s}{u_*} = f\,(z/z_0) \tag{5}$$

$$z_0 = z_0(\nu/u_*,\; u_*^2/g). \tag{6}$$

We obtain $f(z/z_0)$ from results for flow over a smooth surface. For z_0 we choose a simple expression which has the proper limiting forms for small and large u_*. Although some arbitrariness is introduced in the precise form z_0 should take, qualitative features of the resulting profile are informative. In particular, (5) and

(6) give

$$u'(z) = \frac{u_*}{z_0} f'(z/z_0). \tag{7}$$

At a fixed value of z we have from (2) and (4)

$$u'(z) \rightarrow \begin{cases} u_*^2/\beta\nu \quad f'(z/z_0) \quad \text{(smooth surface)}, \\ g/u_* m \quad f'(z/z_0) \quad \text{(rough surface)} . \end{cases} \tag{8}$$

If the dependence of f' upon u_* is weak, (8) suggests that the shear will first increase with u_* (and therefore with stress) and then fall off as the surface roughens. This will later be shown possible near the surface. As noted below, however, for sufficiently large z, f reverts to logarithmic form, so that from (7), $u'(z) \propto u_*/z$. Thus, outside the interfacial sublayer shear always increases with stress.

For conditions of neutral stability and smooth surface, Liu, et al. (1979) proposed, with some experimental justification, the profile

$$\frac{u - u_s}{u_*} = \begin{cases} \frac{1}{k} \log \left(\frac{z\, u_*}{\beta\nu}\right), & z > 47\ \nu/u_* \\ 16\ (1 - \exp\ (- \frac{z\, u_*}{16\nu})), & z \leq 47\ \nu/u_* \end{cases} \tag{9}$$

Equation (9) also applies fairly well to the near-bottom current data of Chriss and Caldwell (1982). (See Figure 1). From (9), (5), and (2) we have

$$f(x) = \begin{cases} \frac{1}{k} \log x, & x > 427.3 \\ 16\ (1 - \exp \frac{-\beta}{16} x), & x \leq 427.3 \end{cases} \tag{10}$$

A single expression which closely approximates (10) is

$$\tilde{f}(x) = \frac{1}{k}\,(1+(\beta k-1)e^{-nx})\,\log(1+x), \tag{11}$$

where n=0.0115 is a fit constant. This particular value of n was found numerically to minimize the root mean square error

$$\varepsilon = ||\, f\,(x) - \tilde{f}(x)\,||/||\, f(x)\,||, \qquad 0 \le x \le 500. \tag{12}$$

For n=0.0115, ε=0.92%, which is well inside the experimental uncertainty of (9). Figure 1 compares f(x) calculated from equation (10) with $\tilde{f}(x)$ from (11).

In order to complete the wind profile we must adopt a functional form for z_o. The simplest form which exhibits the proper smooth and rough flow limits is

$$z_o = \beta\nu/u_* + m\, u_*^2/g. \tag{13}$$

(See Figure 2). Equations (13), (5), and either (10) or (11) completely specify the generalized wind profile.

3. RESULTS AND COMPARISON WITH DATA

Direct comparison of the generalized wind profile with data for an air-water interface is not possible due to an apparent lack of wind speed at a set of points highly resolved with respect to z. There are, however, drag coefficent data available for comparison. The transition from smooth to rough flow might reasonably be defined as the point at which (13) attains a minimum value. We find from (13)

$$z_{o\,min} = 3\ (\beta^2\nu^2 m/4g)^{1/3} \tag{14}$$

$$\text{for}\quad u_* = (\beta\nu g/2m)^{1/3}\ . \tag{15}$$

Taking m = 0.02 and ν (air) = 0.15 cm^2/sec, we find $z_{o\,min} = 3.3 \times 10^{-3}$ cm for $u_* = 7.4$ cm/sec. This compares with $u_* = 6.2$ cm/sec suggested by Figure 7 of Kondo (1975). It is interesting to note the minimum thickness of the interfacial sublayer (the region where the wind profile is non-logarithmic). From (10) the layer thickness is 427 z_o. The minimum thickness of the layer is thus 1.43 cm.

Another comparison with data can be made through the drag coefficient as a function of wind speed:

$$C_{10} = (u_*/u_{10})^2 \tag{16}$$

where the subscript 10 refers to a height of 10 meters. Figure 3 compares the result from the present model to data summarized by Kondo (1975) and by Phillips (1977). The former reference does not indicate the degree of scatter in the data, whereas the latter cites older data.

Another interesting prediction of the model (for which there is apparently no data for comparison) concerns the variation of shear with applied stress in the interfacial sublayer. From (7) and (10) we find for $z \to 0$,

$$u'(0) = \beta \frac{u_*}{z_o} \tag{17}$$

$$= \frac{\beta u_*^2}{\beta\nu + m\, u_*^3/g} \quad ,$$

where the second equality is taken from (13). The surface shear first increases as u_*^2 and then falls off as u_*^{-1}. According to this result, the maximum surface shear is

$$u'(0)_{max} = \frac{1}{3} \left(\frac{4\, g^2 \beta^2}{m^2\, \nu}\right)^{1/3} \tag{18}$$

for $$u_* = \left(\frac{2\, g\, \beta\nu}{m}\right)^{1/3} . \tag{19}$$

For parameter values quoted above, the surface shear attains a maximum value of 306 sec^{-1} for u_* = 11.74 cm/sec. The meaning of this overturning of the stress-shear relation (if it is in fact real) is that the surface roughens to such an extent that turbulence is locally increased and the shear is more effective in transferring stress to the surface.

The thickness of the region in which the negative stress-shear relation might exist can be estimated as follows. From (7) and (10b) we find

$$\frac{\partial}{\partial u_*} \log u'(z) = u_*^{-1}\left(1 - \frac{u_*\, z_o'(u_*)}{z_o}\left(1 - \frac{\beta z}{16 z_o}\right)\right). \tag{20}$$

In the limit of rough flow (4) implies $u_* z_o'(u_*)/z_o \to 2$. Then for rough flow, a negative stress-shear relation results for $z/z_o < 8/\beta = 72.7$. This layer is approximately the lower one-sixth of the interfacial sublayer, and for parameter values assumed, has a thickness ranging from 0.24 to 3.7 cm as u_* increases from 7 to 50 cm/sec. These u_* values give a reasonable coverage of rough flow conditions.

If the hypotheses and conclusions of this note are correct, one should re-examine the relation between linear wave-growth models (Miles, 1962; Valenzuela, 1976) and the real live air-sea interface. These models show reasonable agreement with growth rate data for wavelengths of 4 cm and less with u_* in the range 10 to 50 cm/sec. The agreement is poor at larger wavelength. Both of these models assume a wind profile appropriate to smooth laminar flow near the surface (i.e., $\tau = \rho\nu\, u'(0)$). After at most a few seconds, however, the surface would be roughened by capillary waves, implying less shear in the wind profile according to the present model.

According to Kondo et al. (1973), roughness begins to occur for root mean square waveheights as low as 0.14 cm. Herein lies a paradox: the waves may still be small enough in amplitude to appear linear, but they may have modified the wind profile that created them! Viewed this way, the wind-water wave system becomes nonlinear at a very small amplitude. On the other hand, one could start with a pre-roughened surface and consider linear perturbations to a modified velocity profile and shear-stress relation such as that proposed here. It would be most interesting to examine linear growth rates for wavelengths in the 1-10 cm range to see if some of the discrepancies normally attributed to nonlinear wave-wave interactions in the water might be accounted for by altered velocity profiles and shear-stress relation in the air and water.

Postscript: During the preparation of this note, Mollo-Christensen and Ramamonjiarisoa (1982) published data indicating that capillaries do indeed alter the wind profile above them. They also suggested that an altered profile (of unspecified form) be taken into account when calculating wave growth rates.

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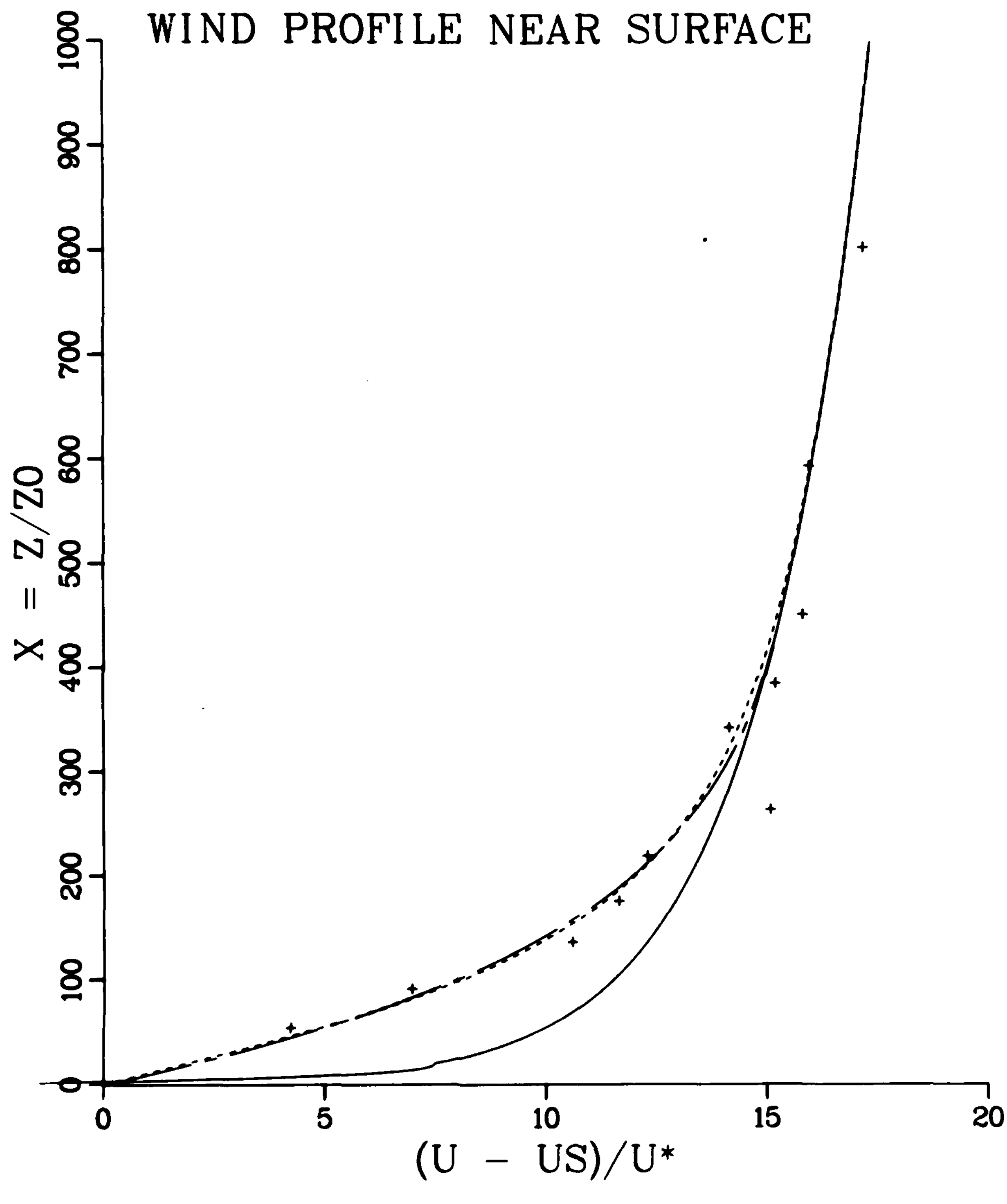

Figure 1. Solid curve: logarithmic wind profile (1). Dot-dash: "interfacial sub-layer" model (10) of Liu et al. (1979) representing data. Dotted curve: best fit from (11). x = 1000 typically represents a height of a few centimeters. Crosses: data from Fig. 1 of Chriss and Caldwell (1982) for $u_* = 0.46$ cm/sec and $z_o = 2.4 \times 10^{-3}$ cm.

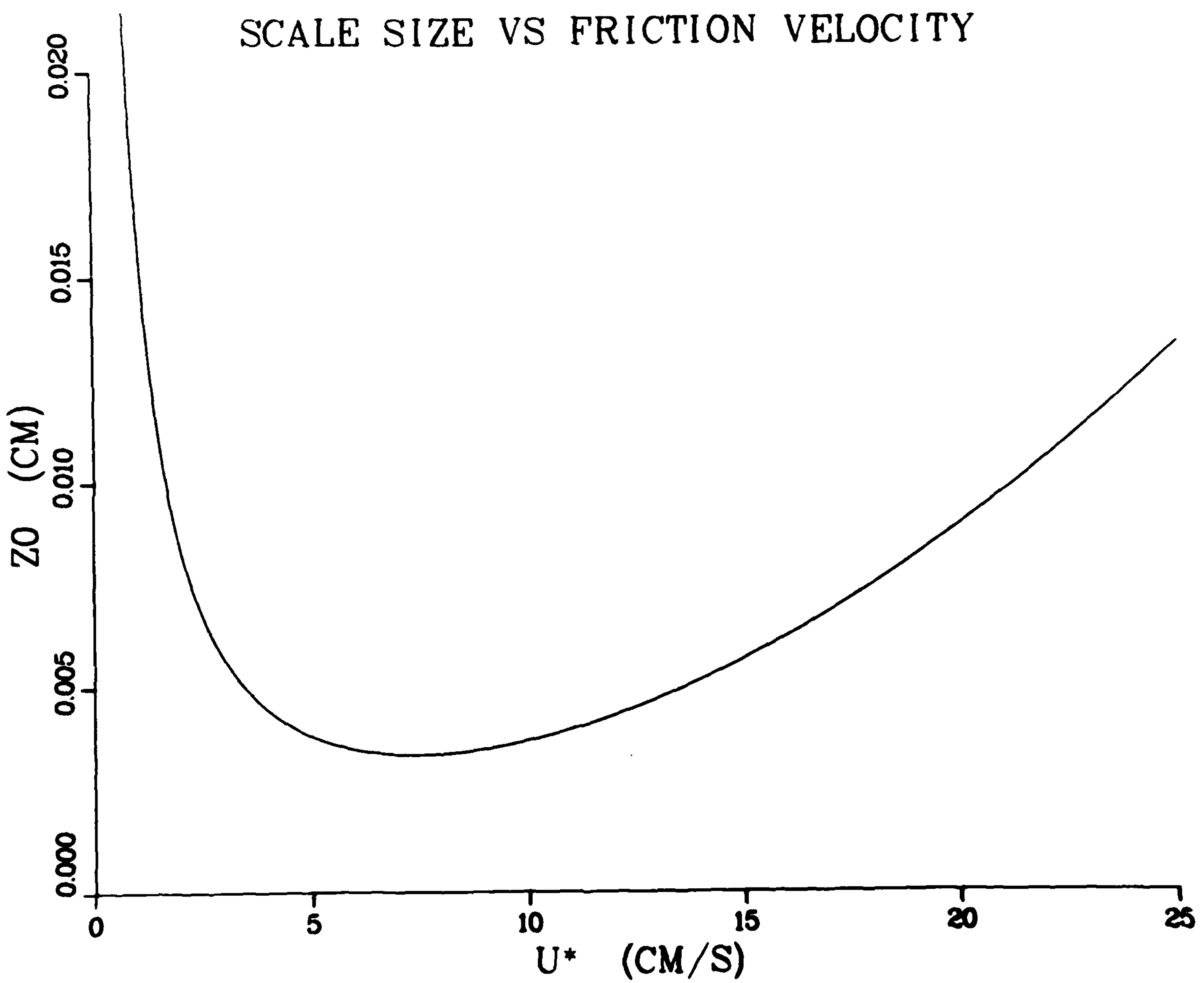

Figure 2. Variation of scale size with friction velocity (eq. (13) with $m = 0.02$) illustrating smooth flow behavior at small u_* and rough flow behavior at large u_*.

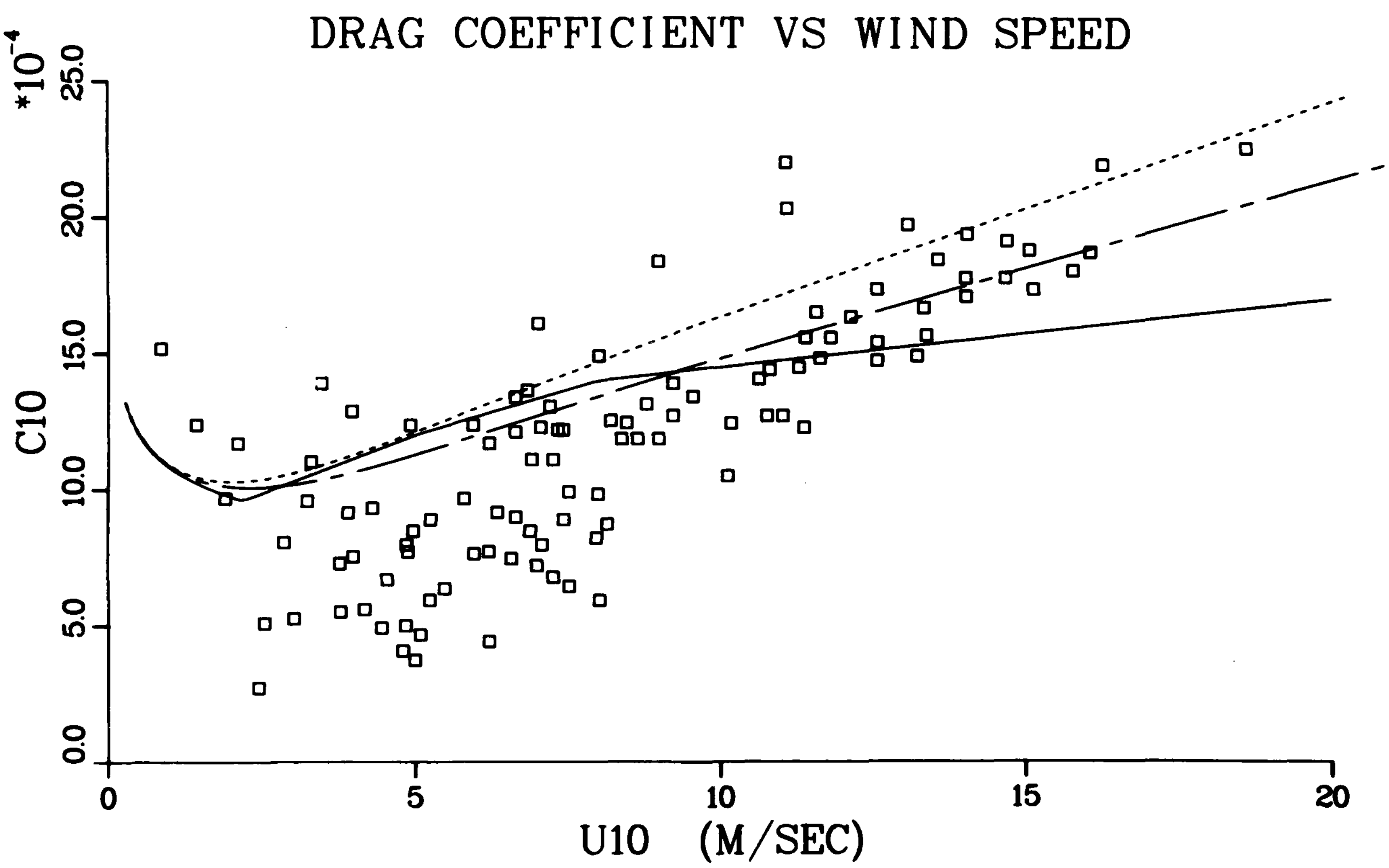

Figure 3. Drag coefficient as a function of wind speed at a height of 10 meters. Squares: pre-1960 data quoted by Phillips (1977). These points indicate the degree of scatter in the data resulting partly from atmospheric stratification. Solid curve: Kondo's (1975) fit to more recent data. The degree of scatter is not specified. Dotted curve: result of present model with m = 0.01 in (13). Dot-dash: result for m = 0.02

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